New Issues In Low Energy Dynamical Supersymmetry Breaking

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(Received October 1995)

Comparatively simple models, with low energy structure similar to that of the MSSM, but with far fewer arbitrary parameters, can be constructed in which supersymmetry is dynamically broken at low energies. The phenomenology of these models is somewhat different than that of the usual scenario with supersymmetry broken in a hidden sector.

§1. Introduction

I would like to report on some work done recently with Michael Dine, Yossi Nir and Yuri Shirman on models in which supersymmetry breaking occurs dynamically and is communicated to the squarks, sleptons and gauginos via renormalizable gauge interactions [1)]. Our motivations for constructing such models were threefold.

1. Dynamical Supersymmetry Breaking (DSB) has the potential to explain the hierarchy between the scales of weak and gravitational interactions [2)].
2. If supersymmetry breaking is communicated to the squark and sleptons via gauge interactions, sufficient degeneracy to be compatible with Flavor Changing Neutral Current Constraints (FCNC) is automatic.
3. Since we do not know either the mechanism or the scale of supersymmetry breaking, we should explore as many possibilities as we can.

For the technicolor enthusiasts in the audience, let me add a couple of other motivations for exploring models of low energy DSB.

1. Interesting nonperturbative effects occur in these models, which are under theoretical control.
2. One might try and also explain dynamically in a DSB model puzzling features of both the standard model and the MSSM such as the quark and lepton mass spectrum and the number of families. Such a model would have the same theoretical attraction as technicolor. Supersymmetry has the advantage of both enlarging and constraining the dynamical possibilities. While in technicolor models it is hard to see how to eliminate unwanted exact chiral symmetries, in supersymmetric theories there are naturally light scalars and Yukawa couplings.

Our model building strategy to date has been simple but not elegant–our models have three "sectors". The superpotential does not mix the different sectors–only gauge interactions connect them. In the heaviest sector, called the "supercolor" sector, supersymmetry is dynamically broken via gauge interactions at a scale of $\sim 10^6 - 10^7$ GeV. We have recently discovered a large number of new possibilities for

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this sector [1], and there are clearly a huge number of still unexplored possibilities. To communicate supersymmetry breaking, we gauge a global symmetry of the supercolor sector (the "messenger" gauge group). We then add a few superfields carrying the messenger symmetry and having superpotential couplings with particles carrying ordinary color and electroweak gauge interactions (the messenger sector). These ordinary gauge interactions feed down supersymmetry breaking radiatively into the ordinary sector.

The resulting models are somewhat different from the usual Minimal Supersymmetric Standard Model (MSSM); the major differences are summarized in the following table.

	Low Energy DSB	**MSSM**
Supersymmetry Breaking	Spontaneous, nonperturbative $M_S \sim M_p e^{-4\pi^2/g^2}$	"Soft" (assumed to occur in "hidden" sector) at $\sim 10^{11}$ GeV
Messenger of SUSY Breaking	gauge interactions at $10^4 - 10^6$ GeV	gravitational, Planck scale interactions at 10^{19} GeV
Lightest Supersymmetric Particle	gravitino $m_{3/2} \sim 1$ keV	mixture of photino, Zino, higgsino
Superpartner Masses	Calculable in terms of 2 parameters arising in renormalizable Lagrangian	~ 100 free "soft" parameters reducable to ~ 4 parameters via theoretical assumptions
FCNC	small due to accidental approximate flavor symmetry	assumed to be small, requires squark, slepton degeneracy
Cosmology	gravitino "hot" dark matter possible TeV mass cold dark matter	LSP cold dark matter, gravitino decays a problem for nucleosynthesis, gravitationally coupled light scalars a serious problem

§2. The Dynamical Supersymmetry Breaking Sector

There is a simple criterion for models which exhibit dynamical supersymmetry breaking [3]. If a theory has no flat directions, and it has a global symmetry which is spontaneously broken, then supersymmetry is spontaneously broken. Here I describe a new model which satisfies this criterion and which can serve as a simple supercolor sector.

The gauge group is $SU(6)\times U(1)\times U(1)_m$. (The $U(1)_m$ symmetry plays the role of the "messenger" gauge group. This theory has a stable supersymmetry breaking ground state whether or not the $U(1)_m$ is gauged.) The chiral superfields are:

$$A_{+2,0} \quad F_{-5,0} \quad \bar{F}^{\pm}_{-1,\pm 1} \quad \bar{F}^{0}_{-1,0} \quad S^{\pm}_{+6,\pm 1} \quad S^{0}_{+6,0}, \tag{2·1}$$

($A = 15$, $F = 6$, $\bar{F} = \bar{6}$ and $S = 1$ of $SU(6)$, the subscripts give the $U(1)$ charges.) For the superpotential we take

$$W = \lambda A\bar{F}^{+}\bar{F}^{-} + \gamma F(\bar{F}^{+}S^{-} + \bar{F}^{-}S^{+}) + \eta F\bar{F}^{0}S^{0}. \tag{2·2}$$

Here we have imposed a discrete symmetry,

$$A \to A, \qquad F \to +iF, \tag{2·3a}$$
$$\bar{F}^{\pm} \to -i\bar{F}^{\mp}, \quad \bar{F}^{0} \to -i\bar{F}^{0}, \tag{2·3b}$$
$$S^{\pm} \to S^{\mp}, \qquad S^{0} \to S^{0}, \tag{2·3c}$$

under which the $U(1)_m$ gauge fields change sign. This discrete symmetry guarantees that a D term for $U(1)_m$ will not be generated, which is good because in earlier model building attempts with a $U(1)$ messenger group [5] the generation of a D term required that the messenger sector be complicated and slightly fine-tuned to avoid undesirable symmetry breaking patterns. This theory also has a nonanomalous, global $U(1)_R$ symmetry. By looking at the effective theory along various directions in field space, it is possible to show that gaugino condensation in an unbroken $SU(2)$ subgroup of the $SU(6)$ gives a term in the effective superpotential which leads to spontaneous breaking of this R symmetry and of supersymmetry. The supersymmetry breaking minimum may be systematically studied in the limit where the superpotential couplings are weak, and we find that the vev's of the fields have the following form:

$$A = \begin{pmatrix} \sqrt{\frac{v^2}{2}+a^2}\,\sigma_2 & & \\ & a\sigma_2 & \\ & & a\sigma_2 \end{pmatrix}, \quad S^0 = c, \tag{2·4a}$$

$$\bar{F}^{-} = \begin{pmatrix} v\\0\\0\\0\\0\\0 \end{pmatrix}, \quad \bar{F}^{+} = \begin{pmatrix} 0\\v\\0\\0\\0\\0 \end{pmatrix}, \quad \bar{F}^{0} = \begin{pmatrix} 0\\0\\b\\0\\0\\0 \end{pmatrix}, \quad F^{0} = \begin{pmatrix} 0\\0\\b\\0\\0\\0 \end{pmatrix}, \tag{2·4b}$$

and all other vev's vanish. A linear combination of messenger hypercharge and a subgroup of the $SU(6)$ is unbroken in this ground state.

§3. The Messenger Sector

Although it is nice to have an explicit model of the supersymmetry breaking sector, for the foreseeable future we are unlikely to have direct experimental access

to this physics, but at best expect to probe the spectrum of superpartners of the already observed particles. In our model building approach, supersymmetry breaking is transmitted to the ordinary superpartners via an intermediate sector, the "messenger". The ordinary superspectrum then is quite insensitive to the details of the supercolor sector, but does crucially depend on the choice of messenger sector. Fortunately, we find that an extremely simple choice here will lead to acceptable superpartner masses.

In addition to the chiral superfields of the previous section, we include a gauge singlet X, two fields ϕ^+ and ϕ^- with messenger charge ± 1, and vector-like quark and lepton fields, q, $\bar{q}$, ℓ and $\bar{\ell}$ carrying ordinary $SU(3)\times SU(2)\times U(1)$. For this set of fields we take the superpotential to be

$$W_X = k_1\phi^+\phi^- X + \frac{1}{3}\lambda X^3 + k_3 X\bar{\ell}\ell + k_4 X\bar{q}q \; . \tag{3·1}$$

At two loops, the scalar components of ϕ^+ and ϕ^- gain a mass squared which is negative for a range of parameters:

$$m_\phi^2 = -\frac{1}{2}\left(\frac{\alpha_m}{\pi}\right)^2 m_\chi^2 \ln(\Lambda_6^2/m_\chi^2). \tag{3·2}$$

Here Λ_6 is the scale of the $SU(6)$ theory; it is roughly the scale where the χ mass is determined.

As a result, the effective potential for $\phi^\pm$ and X has the form, ignoring for a moment the terms involving q, ℓ and $\bar{q}, \bar{\ell}$,

$$m_\phi^2\left(\left|\phi^+\right|^2 + \left|\phi^-\right|^2\right) + \left|k_1 X\phi^+\right|^2 + \left|k_1 X\phi^-\right|^2 + \left|k_1\phi^+\phi^- + \lambda X^2\right|^2 \; . \tag{3·3}$$

At the minimum of this potential, ϕ^+, ϕ^-, X and F_X have non-zero vev's. For sufficiently small λ, this point is a minimum with zero vev's for the fields q, $\bar{q}$, ℓ and $\bar{\ell}$. Note that had there been a Fayet-Iliopoulos term at one loop for $U(1)_m$, F_X would have been zero.

With nonzero F_X and $\langle X\rangle$, the fields q, $\bar{q}$, ℓ and $\bar{\ell}$ all obtain mass and have a nonsupersymmetric mass spectrum, with some scalars lighter than their fermionic superpartners and some heavier.

§4. Supersymmetry Breaking in the MSSM Sector

We can now integrate out the supercolor and messenger sectors, and consider the masses of squarks, sleptons and gauginos. Loop corrections to these masses arise when we integrate out the fields q, $\bar{q}$, ℓ and $\bar{\ell}$. At one loop, for small λ, we obtain (Majorana) masses for the $SU(3)$, $SU(2)$ and $U(1)$ gauginos to lowest order in F_X:

$$m_{\lambda_i} = c_i\, \frac{\alpha_i}{4\pi}\, \Lambda \; , \tag{4·1}$$

where $c_1 = \frac{5}{3}$, $c_2 = c_3 = 1$, and the parameter Λ,

$$\Lambda = \frac{F_X}{X}, \tag{4·2}$$

sets the scale for *all* of the soft breakings in the low energy theory. Masses squared for the squarks and sleptons appear due to gauge interactions at two loops. They are given by

$$\tilde{m}^2 = 2\Lambda^2 \left[C_3 \left(\frac{\alpha_3}{4\pi}\right)^2 + C_2 \left(\frac{\alpha_2}{4\pi}\right)^2 + \frac{5}{3}\left(\frac{Y}{2}\right)^2 \left(\frac{\alpha_1}{4\pi}\right)^2 \right]. \qquad (4\cdot3)$$

Here $C_3 = 4/3$ for color triplets and zero for singlets; $C_2 = 3/4$ for weak doublets and zero for singlets, and Y is the ordinary hypercharge. There is no general reason for these masses squared to be positive, and finding positive squark masses squared is a nontrivial constraint on the allowed messenger sector. Fortunately they turn out positive for this simple messenger sector.

Note the structure of the theory at this level. Squarks are the most massive scalar fields, by roughly a factor of three compared to slepton and Higgs doublets. Slepton singlets are the lightest scalar fields, by still another factor of order three. Gluinos have masses comparable to squarks, while the Majorana component of the wino mass matrix is comparable to that of the doublets. Note also that the strict degeneracy of squarks and of sleptons of the same gauge quantum numbers is only broken by effects of order quark or lepton Yukawa couplings. We will see that experimental constraints give masses for squarks and gluinos in the $200 - 300$ GeV range. This means that $\Lambda \sim 10 \quad TeV$. This is the scale of messenger physics. The scale of the hidden sector $SU(6) \times U(1)$ physics is larger by a factor of order $\frac{(4\pi)^2\sqrt{\lambda}}{\alpha_m k_1^2}$, about 10^3 TeV for coupling constants of order one.

§5. Ordinary $SU(2) \times U(1)$ Breaking

Note that in this framework, it seems more difficult than in the MSSM to explain the size of the supersymmetric term $\mu H_U H_D$ term in the superpotential with μ of order the weak scale. This difficulty previously led us to consider a low energy sector more complicated than the MSSM [5),6)]. To simplify the low energy sector, we instead can use a mechanism suggested by Leurer *et al.*[7)]. In this mechanism, in addition to the usual MSSM fields, there is another singlet, S, with only nonrenormalizable couplings. In particular, consider terms in the effective lagrangian of the form:

$$\frac{1}{M_p^2}\int d^4\theta X^\dagger X S^\dagger S + \int d^2\theta \left(\frac{1}{M_p^p} X S^{2+p} + \frac{1}{M_p^m} S^{m+3} + \frac{1}{M_p^n} S^{n+1} H_U H_D \right). \qquad (5\cdot1)$$

The first and second terms can contribute effective negative curvature terms to the S potential, and the field S obtains a large vev, leading to an effective μ term. For example, if $p = 2$, $m = 2$ and $n = 1$, then the μ term is of order $\sqrt{F_X}$ times powers of coupling constants.

We can now analyze the Higgs potential. First, note that a coupling in the superpotential:

$$W_{XH} = \lambda' X H_U H_D \qquad (5\cdot2)$$

leads to a soft-breaking term $m_{12}^2 H_U H_D$ in the higgs *potential.* Here λ' must be

rather small, since these masses should be roughly of order $(\alpha_2/\pi)^2$. This smallness is natural, in the sense of 't Hooft, in that it can arise due to approximate discrete or continuous symmetries. Note that the corresponding contribution to the μ term, however, is *extremely* small, far too small to be of phenomenological significance. Positive soft supersymmetry breaking mass squared terms for H_U and H_D are generated by the same type graphs giving slepton masses. Finally, a negative contribution to the mass squared for H_U arises from loops with top squarks. This contribution, although of three loop order, is somewhat larger than the two loop contributions because it is proportional to the top squark mass squared. We obtain

$$m_{H_U}^2 - m_{H_D}^2 = -\frac{3}{4\pi^2} y_t^2 \tilde{m}_t^2 |\ln\left(\frac{\alpha_3}{\pi}\right)|, \tag{5·3}$$

where $y_t = \frac{m_t}{v_2}$ and, from eqn. 4·3,

$$m_{H_D}^2 \approx \frac{3}{2}\left(\frac{\alpha_2}{4\pi}\right)^2 \Lambda^2. \tag{5·4}$$

The argument of the logarithm is the ratio of the high energy scale, roughly of order Λ, to the stop mass.

To summarize, at energies well below the scale Λ, the theory looks like the usual MSSM, but with well-defined predictions for the soft breaking terms. Indeed, the Higgs potential and all of the soft breakings among the light states are determined in terms of three parameters: Λ, μ, and m_{12}^2 (we view the t quark mass as known.) Other supersymmetry breaking terms, such as trilinear scalar couplings, are also generated but are small.

§6. Summary

A viable DSB model can be found with

1. no hierarchy problem–all mass scales below M_P arise via dimensionless transmutation
2. unifiable ordinary $SU(3) \times SU(2) \times U(1)$
3. additional "supercolor" gauge group, *e.g.* $SU(6) \times U(1)$, and additional "messenger" gauge group, *e.g.* $U(1)_m$
4. a supercolor sector with new chiral superfields carrying supercolor and messenger interactions
5. a simple messenger sector with particles in vector-like representation of messenger group, a gauge singlet, and new vector-like quarks and leptons.
6. radiative squark, slepton and gaugino masses proportional to their gauge couplings squared
7. ordinary superpartner spectrum calculable in terms of two unknown parameters
8. light right handed charged sleptons likely to be found at LEP II
9. no FCNC problem
10. no dangerous pseudo Goldstone bosons
11. light (keV) gravitino

12. no cosmological difficulties.

This is an interesting, viable alternative to the MSSM which is worth serious consideration. However it is in several respects theoretically unsatisfying. The messenger group and the division into three different sectors seem contrived. Perhaps the messenger sector can be eliminated by using Seiberg's idea that some of the ordinary quarks, leptons and gauge bosons are dual to other degrees of freedom [4)], by arranging for quarks and leptons to be light composites, or by finding new DSB mechanisms and models. We might hope to discover a model in which the supersymmetry breaking mechanism involves particles carrying ordinary gauge quantum numbers, perhaps even the ordinary quarks and leptons. In such a model, the scale of supersymmetry breaking might be as low as $\sim 4\pi M_W/\alpha_{\rm wk}$, implying a gravitino mass of ~ 0.1 eV. The next to lightest supersymmetric particle, *i.e.* the lightest neutralino, could then decay into a gravitino and photon with a lifetime of $\sim 10^{-15}$ sec. This lifetime is short enough so that the decay could occur inside particle physics detectors, providing a "smoking gun" signature that the fundamental scale of supersymmetry breaking is low.

§7. Other Directions to Explore?

There are many other possibilities, both for dynamical supersymmetry breaking and for the supersymmetry breaking messenger. One possibility is that the "messenger" sector could be identified with part of the GUT sector. This would imply that the scale of susy breaking is about 10^9 GeV. The resulting low energy model would ressemble the MSSM in many respects, but the usual MSSM GUT predictions for relations among the soft masses could be modified, since the messenger sector is not blind to GUT symmetry breaking. Another possibility is to consider models where nonrenormalizable terms in the superpotential are required for a stable supersymmetry breaking minimum. A simple class of such models has gauge group $SU(N)\times U(1)$, with chiral superfields

$$A \sim \left(\frac{N(N-1)}{2}, N-4\right), \quad \bar{F}_i \sim \left(\bar{N}, 2-N\right), i = 1\ldots N-4, \qquad (7\cdot1a)$$

$$S_a \sim (1,N)\,, a = 1\ldots\frac{(N-3)(N-4)}{2}, \qquad (7\cdot1b)$$

where the representation of the gauge group is in parentheses. The tree superpotential is

$$W_{\rm tree} = \frac{\lambda^{ija}}{m_P} A\bar{F}_i\bar{F}_j S_a \qquad (7\cdot2)$$

while a superpotential

$$W_{\rm dyn} = \frac{\Lambda_N^{\frac{3+2N}{3}}}{\left(A^{N-2}\bar{F}^{N-4}\right)^{\frac{1}{3}}} \qquad (7\cdot3)$$

is dynamically generated [3]. An interesting hierarchy is then generated between the scale of supersymmetry breaking M_s and Λ_N, the scale of $SU(N)$ dynamics, with

$$M_s \sim M_P^{\frac{3-2N}{12+4N}} \Lambda_N^{\frac{9+6N}{12+4N}} \ . \tag{7·4}$$

The scale x of the expectation values of the superfields is

$$x \sim \Lambda^{\frac{3+2N}{6+2N}} M_P^{\frac{3}{6+2N}} \tag{7·5}$$

so

$$M_P \gg x \gg \Lambda_N \gg M_s \ . \tag{7·6}$$

Still more scales could be generated in theories with both renormalizable and non-renormalizable terms in their superpotentials. It seems worth exploring whether some or all of the various widely separated scales appearing in our current ideas about particle physics, (such as the GUT scale, the various quark and lepton masses, the intermediate scale associated with neutrino masses etc.), could be generated in such a model.

Acknowledgements

I would like to thank the organizers for inviting me to this most interesting conference.

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